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Thermal System Verification and Model Validation for NASA's Cryogenic Passively Cooled James Webb Space Telescope (JWST)

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ABSTRACT

A thorough and unique thermal verification and model validation plan has been developed for NASA's James Webb Space Telescope. The JWST observatory consists of a large deployed aperture optical telescope passively cooled to below 50 Kelvin along with a suite of several instruments passively and actively cooled to below 37 Kelvin and 7 Kelvin, respectively. Passive cooling to these extremely low temperatures is made feasible by the use of a large deployed high efficiency sunshield and an orbit location at the L2 Lagrange point. Another enabling feature is the scale or size of the observatory that allows for large radiator sizes that are compatible with the expected power dissipation of the instruments and large format Mercury Cadmium Telluride (HgCdTe) detector arrays. This passive cooling concept is simple, reliable, and mission enabling when compared to the alternatives of mechanical coolers and stored cryogens. However, these same large scale observatory features, which make passive cooling viable, also prevent the typical flight configuration fully-deployed thermal balance test that is the keystone to most space missions' thermal verification plan. JWST is simply too large in its deployed configuration to be properly thermal balance tested in the facilities that currently exist. This reality, when combined with a mission thermal concept with little to no flight heritage, has necessitated the need for a unique and alternative approach to thermal system verification and model validation. This paper describes the thermal verification and model validation plan that has been developed for JWST. The plan relies on judicious use of cryogenic and thermal design margin, a completely independent thermal modeling cross check utilizing different analysis teams and software packages, and finally, a comprehensive set of thermal tests that occur at different levels of JWST assembly. After a brief description of the JWST mission and thermal architecture, a detailed description of the three aspects of the thermal verification and model validation plan is presented.

INTRODUCTION

MISSION DESCRIPTION - Aptly referred to as the 'First Light Machine', the primary purpose of the JWST mission is to observe the early universe at a time when the first stars and galaxies were beginning to form. Outfitted with a passively cryogenically-cooled 18-segment, 6.5 meter primary mirror and a full compliment of near and mid-infrared sensing cameras and spectrometers, JWST will allow astronomers to study the universe as it emerged from the lightless dark ages that followed the big bang.

As an international collaboration among NASA and the European and Canadian Space Agencies, JWST will be launched by an Ariane 5 launch vehicle from Korou, French Guiana. After a six-month journey away from the Earth, JWST will enter orbit around the Earth-Sun L2 Lagrange point at approximately 1.5-million miles from the Earth in the anti-Sun direction. The continuous Earth-Sun angle will allow JWST's telescope and instruments to be shadowed by a large deployable sunshield and to passively cool to cryogenic temperatures. With a large field of regard and almost continuous observing opportunities, JWST will explore a variety of scientific objectives. In addition to viewing the birth of the first stars, JWST will also be specifically suited for studying the evolution of galaxies, the history of the Milky Way, and the origin and formation of planetary systems.

In addition to the technology involved in the deployment and thermal performance of the tennis-court-sized sunshield, JWST will also benefit from the state of the art large format infrared detectors, lightweight Beryllium optics, and cryogenic electronics and mechanisms.

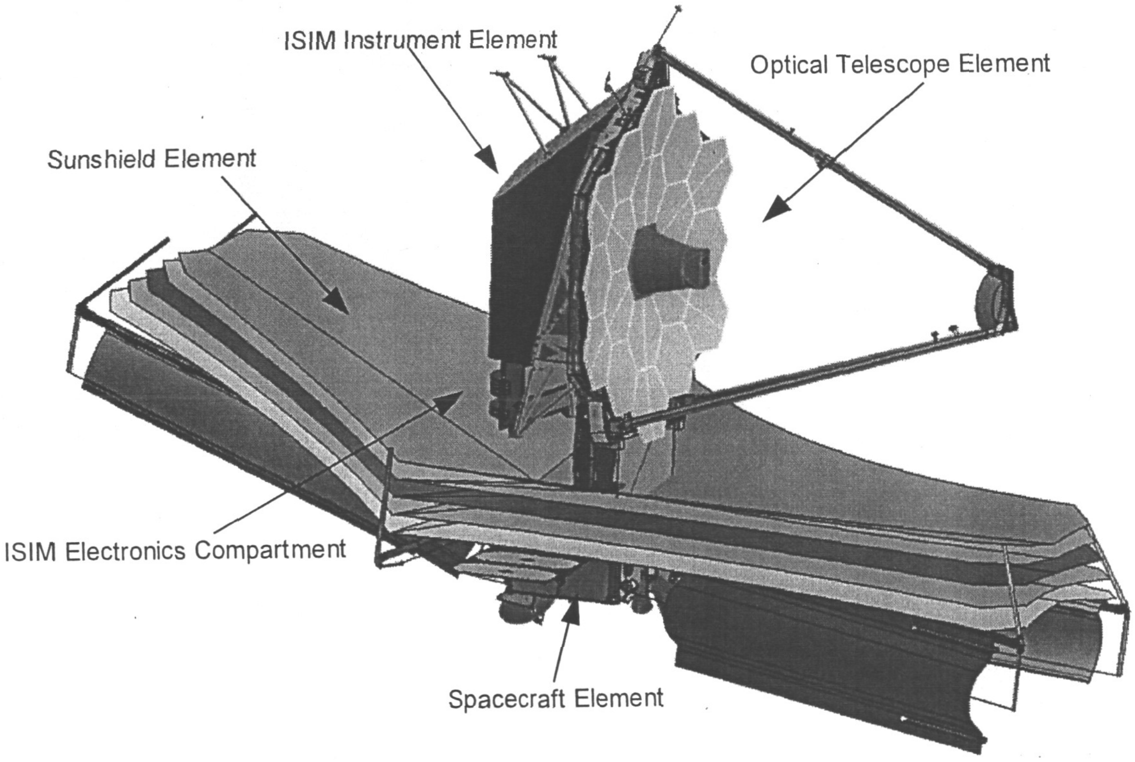

Figure 1. JWST Deployed Observatory

OBSERVATORY THERMAL DESIGN OVERVIEW - A thorough description of the JWST thermal design can be found in Reference 1. Figure 1 illustrates JWST's final on-orbit operational configuration. The process of going from a packaged configuration within the Ariane launch vehicle fairing to a large distributed system requires several complex deployment sequences.

The observatory consists of five primary elements. Dominating the configuration is the large deployed sunshield that consists of five separated aluminized Kapton layers in a V-groove configuration. The sunshield is sized to completely shade the Optical Telescope element (OTE) and Integrated Science Instrument Module (ISIM) element from the Sun over a wide range of viewing angles. The high performance solar attenuation of the sunshield allows the ISIM and OTE to passively cool to below 50 Kelvin. A series of large radiators on the ISIM further cool the instruments to below 40 Kelvin. Conductive isolation from the room temperature spacecraft bus is provided via an isolating deployment tower that also provides separation distance to minimize radiative loading.

VERIFICATION AND VALIDATION OVERVIEW

JWST's thermal verification challenge requires an entirely new approach. Lacking a precedent for a large passively cooled cryogenic observatory without a definitive thermal test to validate thermal performance, a three prong approach has been adopted to ensure that JWST's performs thermally as necessary once on-orbit. The three prongs of the thermal verification philosophy are:

- Strict margin requirements and tracking
- Independent thermal modeling
- Comprehensive thermal test program

The first two aspects of verification are focused on quality control during the design and construction phase of the observatory. A strict and highly formalized process for reviewing and tracking cryogenic thermal design margin combined with a completely independent thermal modeling process essentially starts the

verification process prior to hardware build and integration. These two quality control initiatives are put in place to build confidence in the observatory architecture design and configuration prior to hardware fabrication. Once hardware fabrication commences, model validation begins with a series of thermal tests at the various stages of JWST development and assembly. Missing from this series of tests is one final thermal balance in the deployed configuration. It is intended that the three aspects of verification and validation, which will be further described in detail, compensate for the lack of a final thermal balance test.

CRYOGENIC DESIGN AND MARGIN PHILOSOPHY

The most critical parameter of health for JWST's passive cooling system is the amount of radiator heat lift available while the radiators are at the required cryogenic operating temperature. The heat lift capability is compared against the estimated heat load on the radiators to determine the total heat load margin. Positive heat load margin indicates that the radiators will achieve a temperature below that which is required, indicating good system health. The question then becomes, how much heat load margin is appropriate to ensure cooling success once on orbit. Since JWST's radiator system presents significant mass, volume, and packaging constraints to the overall observatory design, sizing the radiators sensibly, to an appropriate heat load margin, is critical. Vice versa, radiators, that are undersized as a result of too little heat load margin, could result in failure to achieve operating temperature on orbit. Having the proper amount of margin during development is critical since adding radiator late in the design may be prohibitive or require significant observatory architecture changes. These mission impacts necessitate that the required margin be quantified and tracked against predicted margin for all phases of JWST's development.

RADIATOR HEAT LOADS – Heat loads on the radiators come from several sources. For example, of the NIRCAM's 292 milliwatts of total load on its 5.1 m^2 radiator, 229 milli-Watts is allocated instrument load. The allocated load is a specific budget given to the NIRCAM instrument for its internally generated and parasitic heat loads. At the observatory system level, the radiators are designed assuming that the instruments will eventually use their allocation. Each instrument as well as the ISIM is responsible for controlling and estimating their loads and ensuring that they are always within their allocation. As such, the dissipation allocation is considered one of the more definitive loads on the radiators and will be verifiable at the component, instrument, and ISIM level of thermal testing. The other significant load is the 62 milli-Watts of predicted observatory parasitics. These loads are estimated with the observatory thermal models and include radiation loads on the radiators from warmer parts of the observatory, conduction loads from the radiator support system, internal radiative loads, and loads that reach the radiator from warmer parts of the ISIM cavity. The total radiator load is then a combination of estimated and allocated loads. The thermal models also predict the operating temperature of the radiators. Total radiator load capability is then calculated at the maximum allowable radiator temperature.

MARGIN CALCULATIONS – With the total radiator estimated load, $Q_{estimate}$, and total radiator capability, $Q_{capability}$, Margin, M, as a percentage, is calculated by:

$$M\% = \frac{Q_{capability} - Q_{estimated}}{Q_{estimated}} \times 100$$

For JWST's radiator system, margin can also be

$$M\% = \frac{T^4_{required} - T^4_{predicted}}{T^4_{predicted}} \times 100$$

calculated using the predicted and required radiator temperatures:

MARGIN REQUIREMENTS – Prior to entering phase A, the JWST project implemented a high level mission requirement which specified a 50% total radiator heat load margin applicable for the period up to mission critical design review. This margin requirement, atypical for high-level mission requirements, was implemented early in the program in order to better evaluate the different proposed architectures of potential JWST prime contractors. After the critical design review, and once as-built hardware, design drawings, and test results, can be implemented into the thermal models, overall heat load margin will be allowed to drop to 25% prior to launch. This range of margins is consistent with industry practices in the field of cryogenic engineering. (Reference 2). Since 50% is a strict requirement at the program CDR, expected no earlier than in 2006, margin is tracked at the project management level on a monthly basis. Since it is fully expected that margin will decrease as the design and modeling evolves to more detailed levels, a margin reaction limit has been set at 58%. Margin below the reaction alerts the project that the 50% requirement is being approached and that corrective action, e.g. design changes, needs to commence to preserve mission capability. It is a goal of the JWST systems engineering office to lower the required margin prior to launch to no less than 25%. Once thermal model validation is complete and the observatory completes integration and testing, 25% provides the final element of the verification process to account for lingering deficiencies in the modeling, unverified workmanship, and for on-orbit anomalies and failures.

MARGIN TRACKING- Figure 2 illustrates a typical history of aggregate thermal margin for the entire radiator system covering a several month period. This

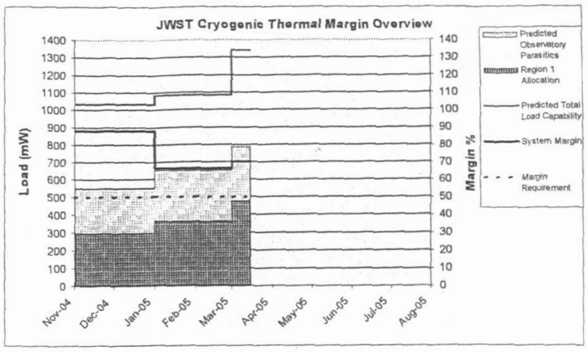

Figure 2. Monthly Margin Tracking Example

graphic provides a quick overview of radiator capability and predicted loads. Loads are further deconvolved to illustrate allocated loads versus observatory model predicted parasitic loads.

INDEPENDENT MODELING

The second key element of the verification philosophy and thermal system modeling quality control is a completely independent thermal modeling effort. JWST's prime contractor, Northrop Grumman, is responsible for all observatory level thermal design and analyses. Since the thermal models for JWST are extremely complex and must predict heat flows accurately to the milliwatt level, a completely independent thermal model is created by NASA's Goddard Space Flight Center. This model is used to crosscheck and evaluate thermal design results, conclusions, and design decisions. The independent thermal model is also created and executed using a different thermal software analysis package further adding to the independence and confidence in the results. Both models use common materials and optical property databases. This use of completely independent thermal models has already uncovered modeling and design assumption errors and will be heavily relied on to confirm JWST's thermal design at all phases of the development cycle. Also adding to the importance of modeling, is the fact that the thermal model results are currently being used to design critical hardware. For example, thermal model predictions for the telescope composite structure are being used to design the fiber lay-up for zero thermal expansion at a specific temperature. Since the current models are not yet validated, independent modeling is used to add confidence to current predictions.

TSS/SINDA MODELING – The JWST project relies on the Systems Improved Numerical Differencing Analyzer (SINDA) and Thermal Synthesis System (TSS) software as the primary thermal analysis and design tools for the observatory. These NASA standard tools are used to model the entire observatory and produce baseline thermal modeling results. These tools are also used to model several of the thermal test configurations. JWST's prime contractor, Northrop Grumman Space and Technology (NGST), is the team responsible for all TSS/SINDA modeling of the observatory.

TMG MODELING - Independent thermal modeling is the responsibility of the Goddard Space Flight Center and is performed using the IDEAS/TMG software suite produced and distributed by Unigraphics Incorporated and Maya Heat Transfer Incorporated. In addition to providing a completely different set of interfaces and tools for model creation, the numerical methods used to solve the radiation and thermal model networks also differ from TSS /SINDA. This provides increased confidence in the independence of the model results. Since GSFC is also responsible for the thermal design of the ISIM, TMG is also used for all instrument and ISIM level thermal analyses. For efficiency, ISIM thermal analysis is performed with the same model used for the independent observatory thermal analyses. It was discovered early in the JWST program that the utilization of boundary conditions, typical of large system analyses, to model observatory sub-assemblies, produced erroneous results. This is due to the complicated and milliwatt level heat flows between observatory elements that need to be modeled at the entire observatory level. Most of the individual instrument providers also use the TMG product, thus helping with configuration control and integration of the ISIM thermal models. GSFC provides thermal design data to the Northrop team that in turn constructs an independent thermal model of the ISIM in the TSS/SINDA environment.

MODEL COMPARISON AND RECONCILIATION – Having two independent thermal models of the JWST observatory is critical to mission success. However, when the results of the two independent models diverge, it is important that the process for reconciling the models accurately uncover the source of the discrepancy. The models are not, for instance, correlated to each other. Once all discrepancies are understood, and the model results still differ, those differences are then believed to be the result of the inherent precision and accuracy of the specific modeling technique. If the differing results still show compliance to all thermal requirements then confidence is gained in the design and the independent modeling effort working as planned. Irreconcilable differences that have one model showing noncompliance and the other compliance, indicates remaining issues with the design of the observatory. This situation occurred during early trade studies when the TMG model was incorporating all of the appendages and cables related to the sunshield system while the TSS/SINDA model had not. When the models could not be reconciled it was uncovered that the overlooked warm appendages had unintended views to the cryogenic side of the observatory thus skewing the observatory thermal performance. Design fixes were identified and the independent modeling effort worked as intended. Figure 3 illustrates early version of the two observatory models and lists the quality control process in place to regularly reconcile and compare the independent thermal predictions.

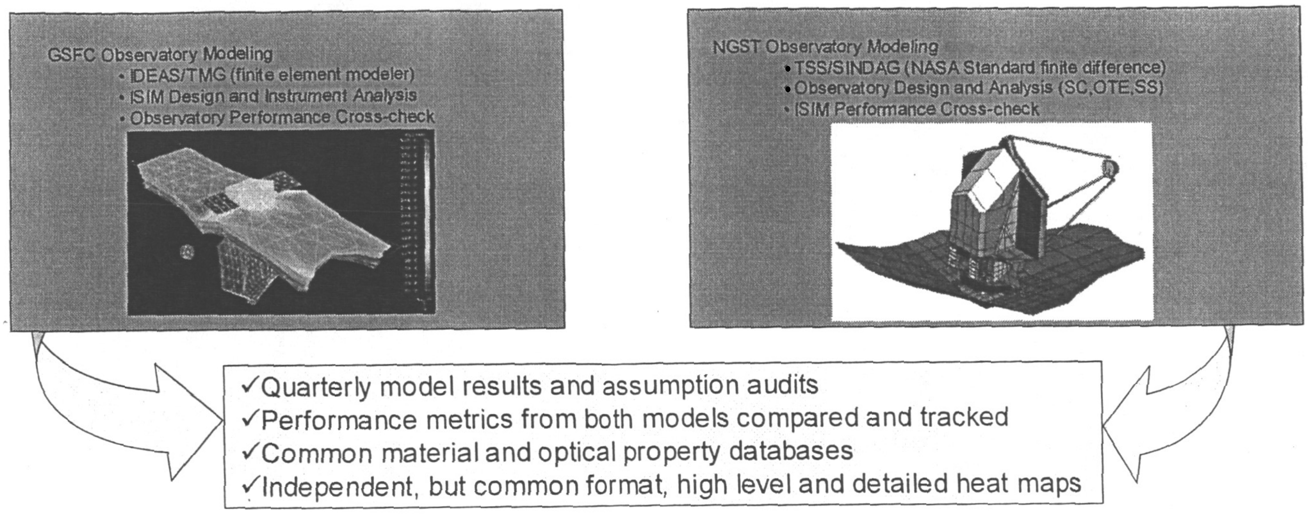

Figure 3. Thermal Model Reconciliation

THERMAL VERIFICATION TESTING

The third aspect of the thermal verification and model validation plan is the comprehensive set of thermal tests that occur at different levels of JWST assembly. As mentioned previously, this complement of tests result from the fact that the JWST is simply too large, in its deployed configuration, to be properly thermal balance tested. Hence, final verification of the JWST TCS will be performed by analysis. The tests serve as key components or anchor points to verifying the performance of the JWST Thermal Control System (TCS) prior to flight.

For purposes of discussion, thermal performance verification is defined as ensuring that all JWST structure, components, instruments, and elements achieve and maintain their required temperature levels throughout the mission lifetime.

Successful verification is relative to a series of thermal requirements. Sources of requirements include the Mission Requirements Document (MRD) as well as a detailed set of lower level thermal verification items. These items were derived as part of an Independent Verification Assessment Team (IVAT) effort in early 2003.

THERMAL VERIFICATION ROAD MAP OVERIEW – The comprehensive set of thermal tests has been organized into a verification flow or "Verification Roadmap". The Verification Roadmap includes test plans at the unit, instrument, element and observatory levels as well as model correlation plans at each level. The goal of a combined look at all testing planned by the various JWST organizations is to produce an integrated path to successful performance, identifying any weaknesses in the thermal test plan, and avoiding redundant tests that may waste program resources.

Figure 5 shows the JWST thermal verification roadmap overview. The flowchart identifies key tests per subsystem, the responsible organization, and the flow of that information into key design efforts.

Figure 6 identifies the series of tests that specifically support the JWST thermal model verification.

A critical part of the verification process is the proper organization of requirements. The MRD requirements have been grouped into eight key requirement areas which are shown in Table 3. The purpose of the groupings is to ensure that the MRD requirements are flowed down to lower level requirements and verification items.

Table 3. Key Requirement Areas

Key Requirement Area	Impact / Source / Relevance
Mission Lifetime	Drives thermal requirements in two areas: the degradation of thermal properties and the degradation in electrical component efficiency (i.e. thermal dissipation increase).
ISIM Cryogenic Temperatures & Margins (NIR detectors & ISIM bench)	Drives lower level requirements on ISIM component dissipations, ISIM parasitic heat loads, and performance of the ISIM radiator system.
OTE Thermal	Driven by observatory sensitivity requirements. The sensitivity requirements drive thermal requirements on OTE dissipations (mechanisms), parasitic heat loads,

	and OTE coatings properties.
Thermal Stability	Derived from observing stability and slew settling requirements for the ISIM and OTE, and from vibration damping material requirements for the spacecraft and OTE tower 1 Hz isolators.
Non-Cryogenic Component Temperatures	Driven by the required compliance with the thermal margins defined in GEVS-SE
Thermal Emissions (Stray Light)	Drive lower level requirements on temperature profiles and surface emissivities for all items on the cryogenic side of the sunshield that have a view into the optical system
MIRI & Dewar	Driven by the requirement for MIRI detector cooling to 6-8K and the MRD requirement for sizing stored cryogen for a 5-year lifetime after commissioning
Observatory Cool Down	Driven by the requirement for JWST commissioning in less than 6 months. Additional requirements on test cool down time are driven by I&T schedule needs

For the purpose of completeness, it is also important to identify and track critical thermal parameter values. These values may be documented in a budget format i.e., a Thermal Loads Budget document, with values verified via test. Examples of these include critical heat dissipations, parasitic loads, thermal material properties and interface thermal couplings assumed in observatory models.

As with all verification flows, the top level and derived requirements have been incorporated into several thermal verification matrices which cover each of the seven key thermal requirement areas. The matrices list each lower level requirement, the verification method, test identifiers, as well as comments on the uncertainty involved in the verification and any risks and liens against the verification approach. In cases where the final verification is by analysis, the matrix also indicates the test "anchor" point that provides confidence in the analysis result (by showing model correlation to test data).

OVERALL TEST PROGRAM – The overall test program is organized into three categories:

- Development Tests
- Unit / Science Instrument Level Tests
- Element & Observatory Level Thermal Tests

DEVELOPMENTAL TESTS – The TCS Development test program includes all tests being performed on non-flight hardware to quantify the performance of key thermal design parameters. The goal of these tests is to reduce the risk of discovering performance issues in higher-level thermal tests where design modifications can have greater cost and schedule impact. Specifically, the test goals are to:

- Characterize cryogenic material properties (structure material conductivity, coating emissivity, SS layer properties)
- Measure key interface conductances (SI thermal strap, SI mount, Dewar mount, OTE actuators, ISIM to OTE mount)
- Quantify parasitic heat loads to the ISIM (harness)
- Measure performance of key blankets/shields (ISIM external MLI, SC core area)
- Quantify thermal performance of critical isolation areas (IEC isolation design)
- Test survivability of critical thermal hardware (SS micrometeoroid)

Figure 7 shows an example of a GSFC coating emissivity test. Testing emissivities at cryogenic temperatures requires Helium shrouds.

UNIT / SCIENCE INSTRUMENT LEVEL TESTS - Overall, there are no significant thermal performance test issues for the electronics boxes mounted on the warm side of the observatory. For these items, the only needed information is the measurement of unit dissipation over the expected operating temperature range.

For electronics boxes on the cryogenic side of the observatory, however, i.e., FPE and ICE boxes with the potential addition of other ISIM/OTE support boxes, accurate measurement of unit dissipation is needed, as well as verification of the dissipation stability expected over the mission lifetime.

The Science Instruments (SI's) will undergo more extensive thermal performance testing. In addition to measurements of dissipation and dissipation stability, thermal testing must quantify the isolation between the FPA's and the SI bench, and the isolation of the FPA's from heat loads resulting from activation of SI mechanisms e.g. filter wheels. In the case of MIRI, SI level testing must include testing of the SI in conjunction with the Dewar.

ELEMENT & OBSERVATORY LEVEL THERMAL TESTS - True observatory level testing of JWST is not possible due to the size of the observatory and the widely varying thermal environments encountered by observatory elements. As a result the final verification of the JWST thermal design relies on a series of element level tests plus tests integrating multiple elements, followed by correlation and analysis using thermal mathematical models.

For the sunshield, thermal verification will rely on testing of a subscale sunshield demonstrator since testing of the full-scale flight sunshield would not yield meaningful results (due to significant sunshield self-coupling off the chamber shrouds for even the largest available thermal vacuum chambers). The subscale thermal balance test will occur in Chamber A of the Johnson Spaceflight Center (JSC). Figure 8 shows a representation of the test utilizing a ½ scale model.

The spacecraft will undergo thermal balance testing at the element level only. The impact of other observatory elements on spacecraft thermal behavior will be captured by ensuring that local sunshield and solar array simulators are present in the spacecraft test. The impact of the spacecraft on the cryogenic observatory elements will be captured via a SC core area simulator in the integrated OTE/ISIM thermal balance tests.

The ISIM will undergo thermal balance testing of the ETU ISIM and flight unit. These tests will be conducted at GSFC, utilizing Chamber 290.

Subsequent to the GSFC tests, both the ETU and flight ISIM will then undergo thermal balance testing with the flight OTE at JSC, Chamber A. The OTE thermal balance tests are performed with the ISIM integrated (ETU ISIM/ flight OTE, and flight ISIM /flight OTE). In each case the TB test will include simulators of other observatory elements (portion of SS surrounding SC, SC core area, tower, IEC radiators, stray light shields) as these are the highest-level TB tests to be performed (the flight OTE / flight ISIM TB test is considered the observatory TB test).

SUMMARY

Although still many years from launch, verification of JWST's unique and unprecedented passive cryogenic cooling system has already begun. A new paradigm has been developed that relies more than ever on the quality of the thermal models to provide final validation of the thermal system's design. This paper has only provided a brief overview of the planning process and initial conceptual plan for the individual thermal vacuum tests that will occur over the next serveral years. Current project plans require that a final thermal verification roadmap be completed late in 2005. The objective of the roadmap will be to demonstrate that all thermal performance and model validation requirements are verified at some point in the program among the variety of JWST organizations and contributors. It is the intent of the authors to routinely update the thermal design and analysis community on the status and progress of the JWST thermal system design and testing.

ACKNOWLEDGEMENTS

The JWST thermal system verification effort is an unprecented challenge that involves several thermal, cryogenic, and systems engineers across several domestic and international organizations. The authors would like to acknowledge the following key individuals for their contributions to JWST and to the information presented herein.

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Robert Mackey – Lockheed Martin JWST Thermal Systems Engineer

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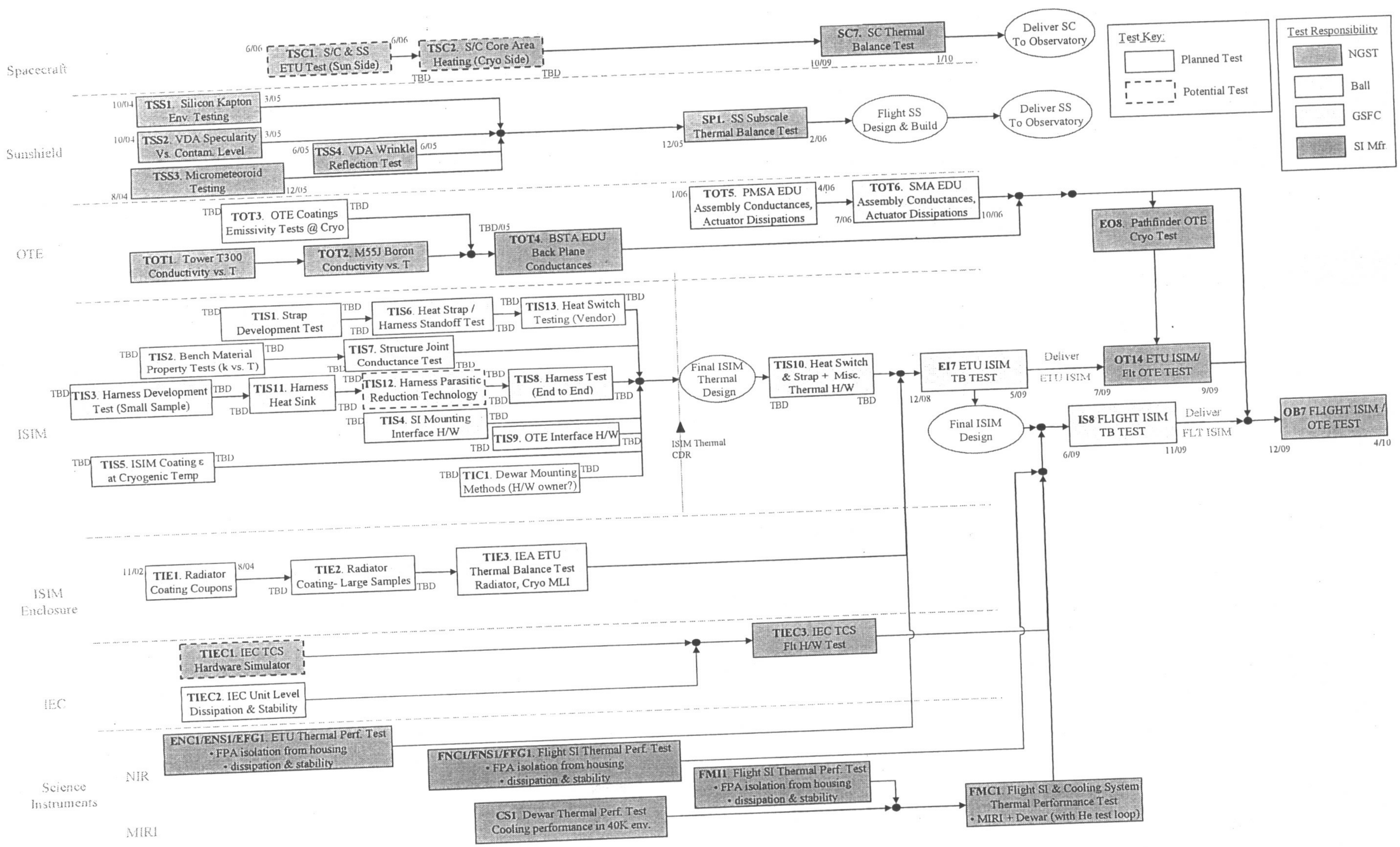

Figure 5. JWST Thermal Verification Roadmap Overview

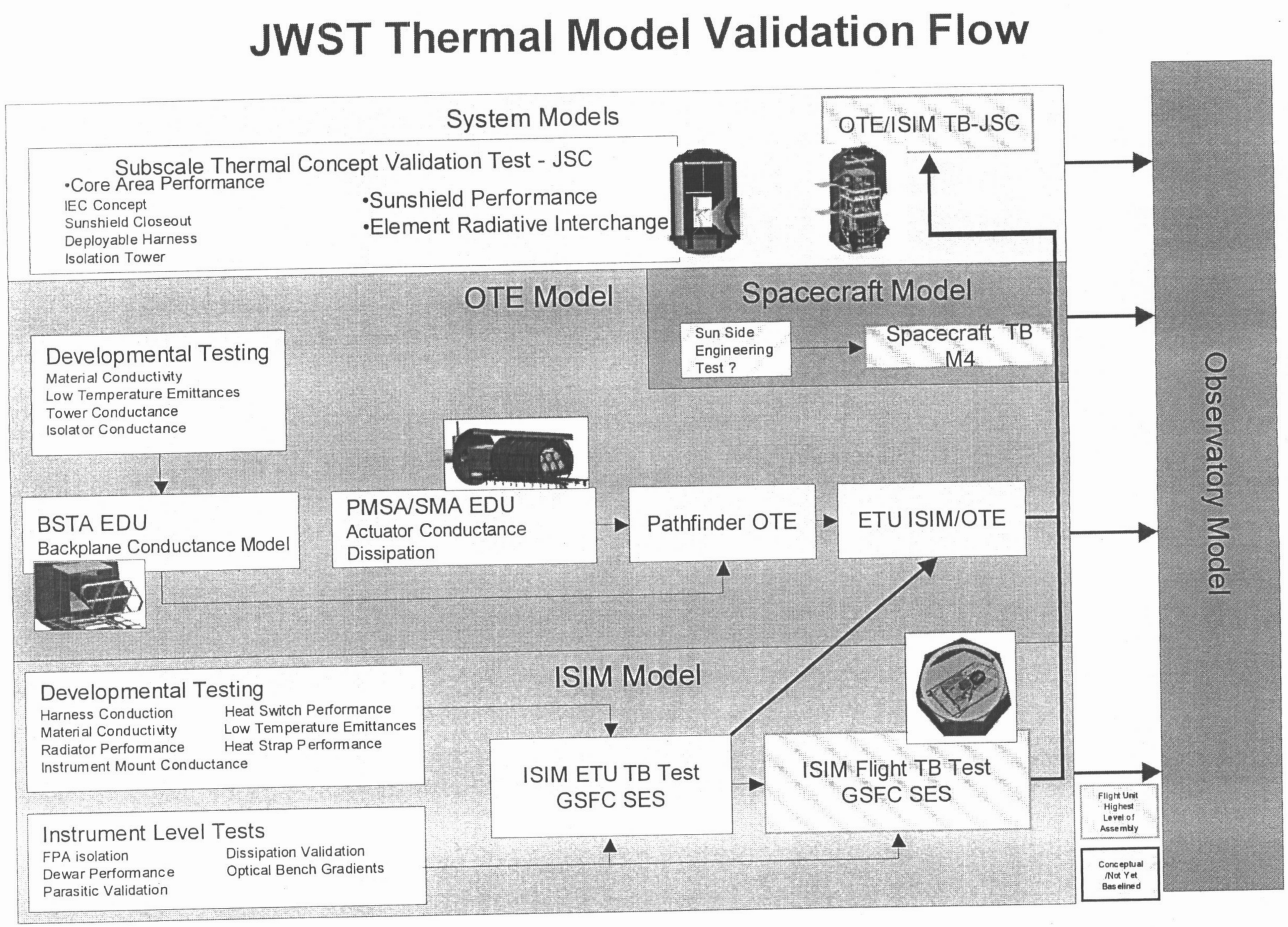

Figure 6. JWST Thermal Model Validation Flow

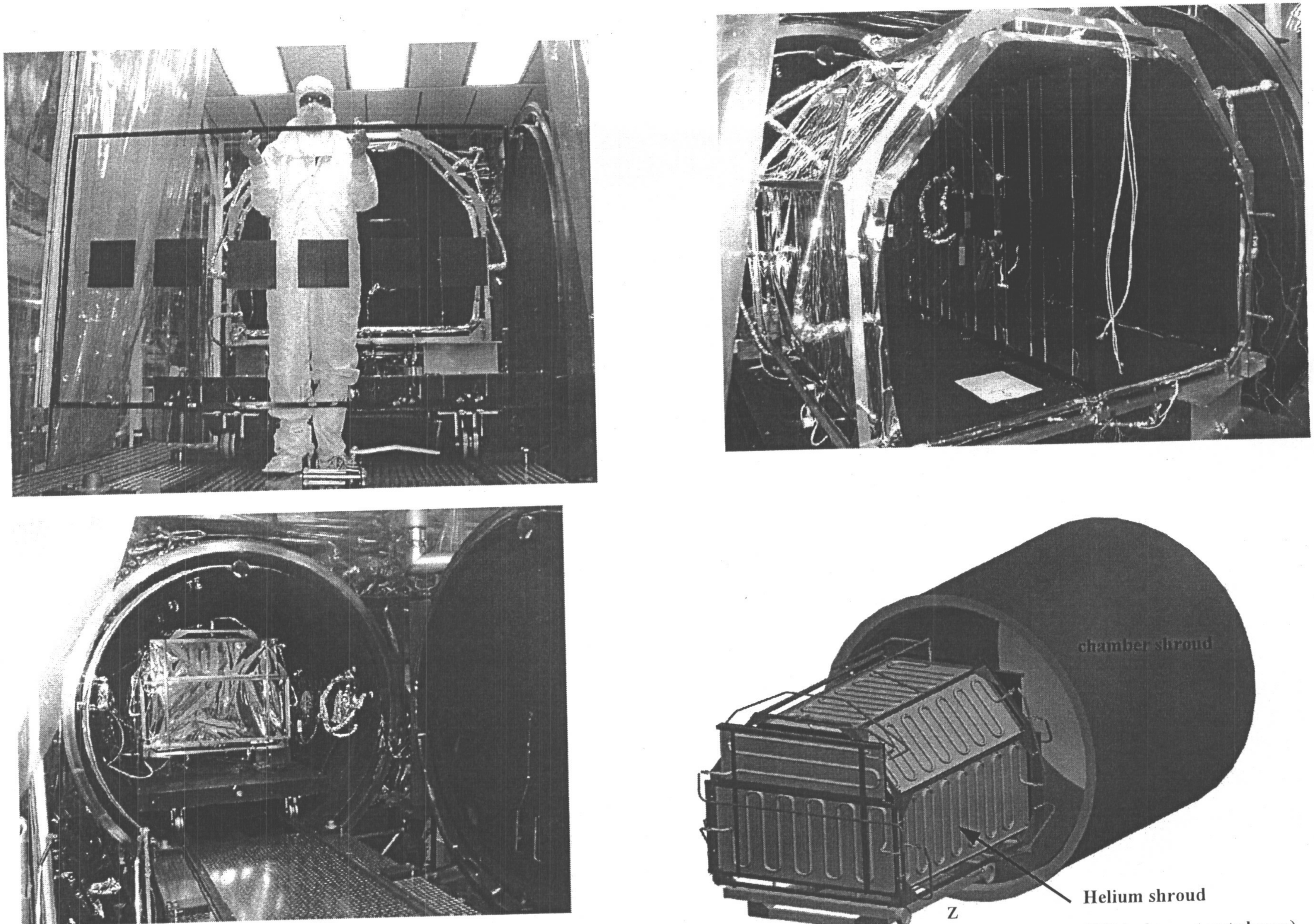

Figure 7. NASA / GSFC Coating Emissivity Test

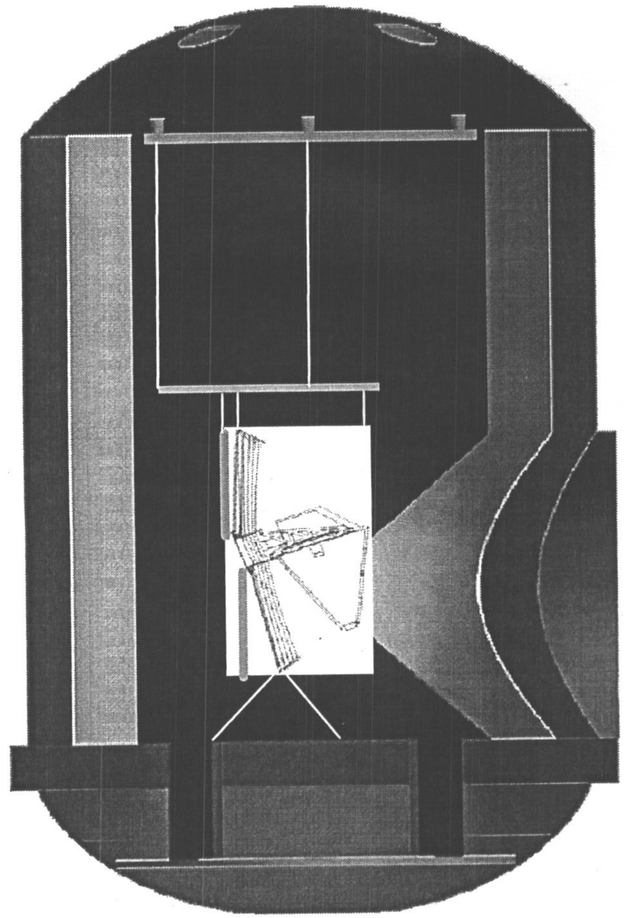

Figure 8. Observatory Subscale Thermal Balance Test at JSC